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Modelling impacts of climate and deposition changes on nitrogen fluxes in northern catchments of Norway and Finland

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Abstract

The Integrated Nitrogen model for Catchments (INCA) was applied to three upland catchments in Norway and Finland to assess the possible impacts of climate change and nitrogen (N) deposition on concentrations and fluxes of N in streamwater in cold regions of Europe. The study sites cover gradients in climate and N deposition from the southern boreal Øygard Brook (2.6 km²) in SW Norway, via the southern/middle boreal Simojoki River (3610 km²) in northern Finland to the sub-arctic Dalelva Brook (3.2 km²) in northern Norway. The INCA scenario simulations included future N deposition scenarios (current legislation and maximum feasible reduction) and climate scenarios for 2050 (ECHAM4/OPYC3; HadCM3) treated separately and in combination. As a result of climate change, the INCA model predicted markedly reduced duration and amounts of snow cover in all catchments. The occurrence of winter rainfall and melting periods was predicted to become more frequent so that more frequent floods in winter will, to a large extent, replace the regular snowmelt flood in spring. At the northernmost catchment, Dalelva, the predicted temperature increase might result in a doubling of the net mineralisation rate, thereby greatly increasing the amount of available inorganic N. At all catchments, the increased N supply was predicted to be largely balanced by a corresponding increase in N retention, and relatively small increases in NO₃⁻ leaching rates were predicted. This dynamic relationship is, however, strongly dependent on the temperature responses of the key N transformation processes modelled. A future reduction in N emissions and deposition, as agreed under current legislation, would have pronounced effects on concentrations of NO₃⁻ in streamwater at the southernmost catchment, Øygard, even following a climate change around 2050. At the more remote Dalelva and Simojoki catchments, the N emission reductions will be small compared to the internal N recycling processes, and climate change will to a large extent offset the effects of reduced N deposition.

Keywords: catchments, surface water, scenarios, climate, hydrology, nitrogen deposition, nitrate leaching

Introduction

Both nitrogen (N) deposition and global change can affect retention and loss of N from catchments to upland surface waters. During the last two decades, there have been substantial national and international efforts to reduce the emissions of S and N compounds in Europe (UN/ECE, 2000; Bull *et al.*, 2001; Skeffington, 2002). Assuming implementation of the Gothenburg protocol and relevant EU directives, the emissions of oxidised and reduced N compounds will be reduced to 1960–70 levels by 2010 (Schöpp *et al.*, 2003). Many of the scenarios developed for future climate in the Nordic countries predict both long-term increases in temperature and precipitation amounts, as

well as increased frequency and severity of extreme events such as floods and storms (Førland *et al.*, 2000; Palmer and Räisänen, 2002). Given that many of the key processes active in terrestrial ecosystems such as the release of N and C from soil organic matter by mineralisation are temperature and moisture dependent, climate-induced changes in N retention and losses from semi-natural ecosystems may be expected (Kirschbaum, 1995; Van Breemen *et al.*, 1998; Wright, 1998). A warmer climate can enhance both acidification and eutrophication by increasing the release of N from soil organic matter to runoff (Wright and Schindler, 1995).

At present the northern parts of Norway and Finland are characterised by long (5–7 months), cold winters with

continuous snow cover and ice cover over rivers and lakes. A snowmelt-induced spring flood in late April–May usually dominates the annual hydrological pattern, whereas less pronounced flow peaks often occur in autumn due to rainfall events. In these areas, a major fraction of the annual NO_3^- loss occurs during these high flow periods (Kaste and Skjelkvåle, 2002; Rankinen *et al.*, 2004). In low-lying near-coastal areas of southern and southwestern Scandinavia, on the other hand, the climate is maritime and winters are often mild with little snow accumulation. In such regions flood peaks occur frequently in all seasons and, usually, there is no distinct spring flood. These temporal patterns change considerably in the future, given the predictions of a warmer and wetter climate in northern Europe.

Nitrogen concentrations and fluxes in rivers are the net result of catchment N sources (non-point sources, atmospheric N deposition, direct effluent discharges, mineralisation) and sinks (plant uptake, immobilisation, denitrification). The process-oriented Integrated Nitrogen model for Catchments (INCA) attempts, quantitatively, to describe these factors by linking hydrology and N inputs from atmospheric deposition, agriculture and populated areas with the microbial processes controlling N behaviour in soils and river reaches (Whitehead *et al.*, 1998; Wade *et al.*, 2002; Wade, 2004). After calibration to a river catchment, the INCA model might be used as a management tool, e.g. to assess the contribution of various N sources to catchment N pools and river NO_3^- concentrations. Additionally, it can be used in assessments of land-phase and in-stream responses to various scenarios of environmental change, including climate change (Wade *et al.*, 2002).

The INCA model has previously been calibrated to two catchments in Norway (Øygard Brook, Dalelva Brook) (Kaste, 2004) and one in Finland (Simojoki River) (Lepistö *et al.*, 2004; Rankinen *et al.*, 2002, 2004). These catchments are typical of upland areas in Norway and Finland with little anthropogenic influence and, together, they provide a good coverage of the climate and deposition gradients observed in the cold regions of Europe. Climate scenarios for this region predict increases over the next 50 years in annual temperatures (1.5–3.0 °C) and precipitation (0–20%) (Hanssen-Bauer, 1999; Førland *et al.*, 2000; FINSKEN, 2003). This may entail significant changes in hydrology, biogeochemical cycling and surface water quality in catchments. In this paper, the INCA model has been applied to the Dalelva, Øygard and Simojoki catchments in Norway and Finland, to evaluate possible impacts of the predicted change in climate and N deposition on snow accumulation, flow patterns, streamwater concentrations and fluxes of N.

Materials and methods

STUDY SITES

Dalelva Brook and Øygard Brook

The Norwegian study sites are located in diametrically opposite parts of the country, Øygard in the south at 58°35'N and Dalelva in the north at 69°45'N (Fig. 1). Nevertheless, their catchment characteristics are comparable in many respects (Table 1). Both Øygard and Dalelva are relatively small (2.6 and 3.2 km², respectively), undisturbed catchments dominated by heathland and mountains. At Øygard, about 20 km from the estuary of the Bjerkreim River (685 km²), the bedrock geology consists of Precambrian migmatites, banded gneisses and anorthosite covered by glacial sediments. Soils are thin and patchy, especially in the upper parts of the catchment, which consists largely of heathland with minor areas of bare rocks (83%); approximately 7% of the total catchment area is occupied by several small lakes (Fig. 1). At Dalelva the bedrock geology is mica schist and micaceous gneiss covered by glacial sediments of similar lithology (Wright and Traaen, 1992). Soils are podsollic, thin and patchy in the upper parts of the catchment. Vegetation is dominated by birch forest up to about 150 m elevation with heathlands and moorlands above. About 15% of the Dalelva catchment is covered with lakes.

Simojoki River

The Simojoki river basin in northern Finland is much larger than the Norwegian study catchments (3160 km²) and lies partly in the southern boreal- and partly in the middle boreal

Table 1. Site characteristics and climate at the study sites. The mean climatic data from Dalelva, Øygard and Simojoki cover the periods 1990–2000, 1993–2000, and 1971–2000, respectively (Kaste and Skjelkvåle, 2002; Drebs *et al.*, 2002).

		Dalelva	Øygard	Simojoki
Catchment area (A_c)	km ²	3.2	2.55	3160
Altitude	m a.s.l.	0–241	185–544	0–200
Land cover:				
- Forest	% of A_c	20	4	39
- Heath/mountains	"	61	83	0
- Peatland	"	4	6	53 ¹
- Agriculture	"	0	0	3
- Lakes	"	15	7	6
Climate (ann. averages)				
- Air temperature	°C	0.2	6.7	0.5–1.5
- Precipitation	m yr ⁻¹	0.63	2.15	0.60

¹includes various types of peatland forests and open peatlands

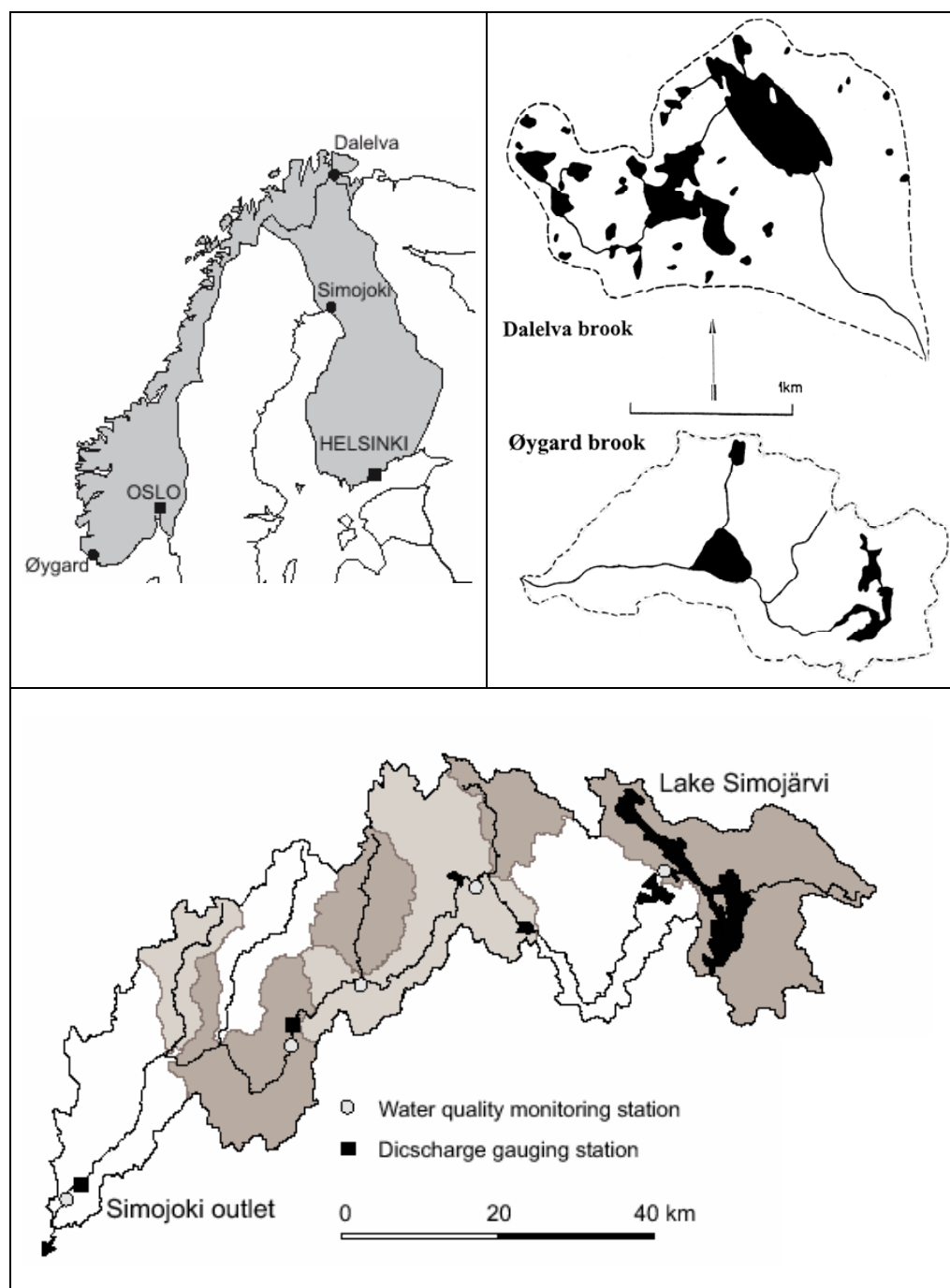


Fig. 1. Maps of Norway and Finland showing the locations of the study sites.

vegetation zone (Fig. 1). The Simojoki River discharges to the Gulf of Bothnia in the Baltic Sea; it is a salmon river without any major point load sources of pollutants. The dominant human impacts in the area are forestry, mainly forest drainage and cutting, agriculture and atmospheric deposition. On average, about 0.5% of the total catchment area is felled annually. The most common bedrock types in

the area are granites and gneisses. Bedrock is covered by till and near the outlet of the river also by river deposits, mainly sand. The land cover is typical for northern Finland, i.e. more dominated by peatlands and forest than the Norwegian study catchments. Peatlands and peatland forests constitute 53% of the Simojoki catchment, whereas nearly 40% is covered by forest on mineral soil (Table 1). Cut areas

cover about 5% of the total forested area, with 1% on organic soil and 4% on mineral soil. Further, about 6% of the river basin area is covered by lakes, whereas agricultural fields cover only 2.7% (Perkkiö *et al.*, 1995). Here, grass cultivation for animal husbandry is the most common form of agricultural production.

CHEMICAL AND HYDROMETEOROLOGICAL CHARACTERISATION

Streamwater chemistry

The period 1993–95 was selected as the basis for the Norwegian INCA calibrations (Kaste, 2004). Water chemistry data from this period comprise weekly samples at Dalelva and fortnightly samples from Øygard. The samples were analysed unfiltered at the Norwegian Institute for Water Research (NIVA) for several hydrochemical determinands. Nitrate (NO_3^-) and ammonium (NH_4^+) were analysed by automated colorimetry, NO_3^- after reduction with cadmium amalgam, NH_4^+ after reaction with hypochlorite and phenol, and total nitrogen (TN) after oxidation with peroxodisulphate. Detection limits for NO_3^- , NH_4^+ , and TN are 1, 5, and 10 $\mu\text{g N L}^{-1}$, respectively. NH_4^+ was not analysed during 1993–95, but the concentration levels are documented by monitoring in 1988, 2000 and during the first half of 2001 (Kaste and Skjelkvåle, 2002).

The Finnish INCA application was based on the period 1994–1996, because these years overlap with the completion of the land-use classification. For the Simojoki River, the N concentration data were obtained from the water quality database operated by the Finnish Environment Institute (SYKE) and regional environment centres. Water samples (12–16 samples yr^{-1}) were taken at the outlet and along the Simojoki River during 1994–1996. Samples were analysed for NO_3^- , NH_4^+ , and TN by the same methods as at NIVA.

Climate and hydrology

At Øygard and Dalelva, daily data on air temperature, precipitation and snow depth were obtained from the nearest monitoring stations operated by the Norwegian Meteorological Institute (met.no, 2001; Kaste and Skjelkvåle, 2002). At the Øygard catchment, mild winters in combination with large precipitation amounts generate a highly variable runoff pattern with frequent flood episodes at all seasons. The Dalelva catchment has a mean annual air temperature around 0°C and annual precipitation amounts around 600 mm yr^{-1} , whereas the corresponding numbers for the Øygard catchment are around 7°C and 2100 mm yr^{-1} , respectively (Table 1). The Dalelva catchment is usually covered with snow for 6–7 months of the year, ranging from the middle of October to late May. Thus, the seasonal runoff

pattern is characterised by very low flows during winter and a distinct snowmelt flood in May–June. At their outlets, both catchments have weirs where discharge is monitored continuously by pressure transducers and loggers operated by NIVA (Kaste and Skjelkvåle, 2002).

In the Simojoki basin, mean annual precipitation was 650–750 mm and mean annual runoff 350–450 mm over the period 1961–1975. There are about 170–180 winter days and the mean annual temperature is +0.5 to +1.5 °C. The duration of the snow cover is from the middle of November to early May. The Simojoki River freezes up at the end of October or the beginning of November, and the ice cover usually breaks up in the middle of May. The Simojoki River has two discharge gauging stations; one at the river outlet and one at the Hosionkoski rapids, in the middle reach of the main river. Mean daily flow at the outlet was 37 $\text{m}^3 \text{s}^{-1}$ during 1965–1990 (Perkkiö *et al.*, 1995).

Atmospheric N deposition and land use

Both the Norwegian catchments have atmospheric deposition as the only external N input (other than N fixation) (Table 2). N deposition data were obtained from the nearest monitoring stations in the Norwegian monitoring programme on long-range transported air pollutants (cf. Kaste and Skjelkvåle, 2002). The data are wet and dry deposition of total inorganic N (TIN), the sum of NO_3^- and NH_4^+ : the wet deposition is determined by the chemical composition and the amount of precipitation, whereas dry deposition is estimated from ambient air concentrations and dry deposition velocities for individual components (Tørseth and Semb, 1998). Whereas N deposition loads at Dalelva are among the lowest in Norway, Øygard is in the part of

Table 2. N deposition scenarios: Present level and estimated future N deposition of oxidised N species (oxi-N) and reduced N species (red-N) given the current legislation (CLE) and maximum feasible reduction (MFR) of N emissions with current technology. The present day is measured deposition during 1993–95 at Dalelva and Øygard and 1994–1996 at Simojoki. The CLE scenario includes the Gothenburg protocol (UN/ECE, 2000) and the National Emission Ceilings (NEC) directive adopted by the European Union. Estimates of future N deposition are modelled by EMEP/IIASA (Schöpp *et al.*, 2003).

	Dalelva		Øygard		Simojoki	
	oxi-N	red-N	oxi-N	red-N	oxi-N	red-N
Present day	1.40	1.30	9.50	7.40	1.51	0.78
CLE	1.02	1.20	5.79	6.63	1.25	0.75
MFR	0.75	0.93	4.20	4.34	0.75	0.61

Norway receiving the highest amount of long-range transported air pollution; average N deposition during 1993–95 (~17 kg N ha yr⁻¹) was six times that at Dalelva. The percentages of each land cover type modelled at the Dalelva and Øygard catchments were obtained from topographic maps, thematic maps and aerial photographs (Kaste and Skjelkvåle, 2002).

In the forested areas of the Simojoki river basin, atmospheric deposition and N fixation are the only external N inputs but agricultural areas are fertilised (Rankinen *et al.*, 2004). Inorganic N deposition (N_{dep}) was estimated using the areal deposition model DAIQUIRI (Kangas and Syri, 2002). Average atmospheric N deposition was 2.3 kg ha⁻¹ yr⁻¹ during 1994–96. For the model application, the most recent satellite image-based land use and forest classification data for Finland were utilised (Vuorela, 1997), supplemented with satellite image-based maps of forest cuttings on mineral and organic soils, provided by the Finnish Forest Research Institute (FFRI).

SCENARIOS USED FOR MODELLING

Atmospheric N deposition

Two scenarios for future changes in N deposition were included: (i) deposition assuming implementation of current legislation (CLE) and (ii) deposition resulting from implementation of maximum feasible reduction (MFR) of emissions. The CLE scenario includes the obligations agreed within the multi-pollutant, multi-effect protocol signed in Gothenburg in 1999 (UN/ECE, 2000) and the limits set by the National Emission Ceilings (NEC) directive that has been adopted by the European Union. The MFR scenario is based on the maximum reduction of N emissions that could be obtained with the currently available technology. N deposition estimates for each study site were derived from a gridded dataset (150 × 150 km) generated by EMEP and IIASA (Schöpp *et al.*, 2003). The CLE scenario entails a 13–27% reduction of N deposition at the study sites compared to the levels in 1993–96 (Table 2). With the MFR scenario, the deposition might be reduced by 38–49%.

Climate

At Øygard and Dalelva, climate scenarios are obtained from the Norwegian RegClim project, which applies dynamic and empirical downscaling techniques to derive regional climate scenarios from global climate models (Hanssen-Bauer, 1999; Førland *et al.*, 2000). The climate scenarios applied at the Norwegian catchments were based on the ECHAM4/OPYC3 model from the Max Planck Institute in Germany and the GSDIO integration, which includes the effects of greenhouse gases, tropospheric ozone, and direct as well as

Table 3. Climate scenarios: Estimated change of air temperature (T) and precipitation (P) for each of four seasons (DJF= December, January, February; etc.) in the year 2050 relative to 2000. Data for Dalelva and Øygard are scaled down from the ECHAM4/OPYC3-GSDIO integration (Hanssen-Bauer, 1999; Førland *et al.*, 2000), whereas the Simojoki application is based on downscaled data from the global HadCM3-gg model from the Hadley Centre, UK (Jylhä, unpubl.; FINSKEN, 2003). The HadCM3-gg data includes two possible scenarios (high/low).

	DJF	MAM	JJA	SON	Year
<i>AT (°C)</i>					
Dalelva	3.5	2.5	1.6	2.6	2.6
Øygard	2.0	1.6	1.6	1.8	1.8
Simojoki, low	2.2	1.1	1.2	1.4	1.5
Simojoki, high	6.0	3.0	3.2	3.8	4.0
<i>AP (%)</i>					
Dalelva	5.2	5.0	1.5	18.2	7.8
Øygard	9.3	1.2	18.2	23.5	13.5
Simojoki, low	8.6	-0.1	4.4	4.7	4.4
Simojoki, high	23.4	-0.2	12.0	12.9	12.0

indirect sulphur aerosol forcing (Roeckner *et al.*, 1999).

In the Simojoki application, two climate change scenarios (low and high) were based on the Hadley Centre model HadCM3-gg and the IS92a emission scenario (Carter *et al.*, 1996). The implication of these scenarios for seasonal temperature and precipitation in Finland has been interpreted by Jylhä (unpubl.) within the FINSKEN project (FINSKEN, 2003; Table 3). Using these seasonal changes, three-year daily temperature and precipitation values were generated for the 2050s and added as input to the Watershed Forecasting and Simulation System (WSFS). The growing season length at the study sites was assumed to increase by nine days for every degree increase in mean annual temperature (Kuusisto *et al.*, 1996).

In Scandinavia, the two global climate models (ECHAM4 and HadCM3) give strong similarities albeit with slightly different projections of seasonal temperature and precipitation changes (Christensen *et al.*, 2001; Haugen and Ødegaard, 2003). According to the Norwegian scenarios for 2000–2050, the mean annual air temperatures are expected to increase slightly more at Dalelva (2.6 °C) than at Øygard (1.8 °C). The highest temperature increase is expected to take place in winter (Table 3). Further, the mean annual precipitation is expected to increase by about 8% at Dalelva and about 14% at Øygard, with the largest increase during autumn (September to November). At Simojoki, the mean annual air temperatures are expected to increase by

1.5 °C (low scenario) to 4.0 °C (high scenario) by 2050. As at Dalelva and Øygard, the largest increase is expected in winter (Table 3). Annual precipitation amounts at the Finnish site might increase by 4% (low scenario) to 12% (high scenario), mostly in winter (December–February).

MODELLING APPROACH

The INCA model

A new version of the process-based and semi-distributed INCA model (Whitehead *et al.*, 1998) has been developed and described in detail by Wade *et al.*, 2002; Wade, 2004). The model integrates hydrology, catchment and river N processes, and simulates daily NO_3^- and NH_4^+ concentrations as time series at key sites, as profiles down the river system, or as statistical distributions. The INCA model requires input of daily time series of air temperature (AT), actual precipitation (P), soil moisture deficit (SMD), and hydrologically effective rainfall (HER; the fraction of P that contributes directly to runoff). Water inputs from melting snow were estimated by a separate snow accumulation and snowmelt model (Vehviläinen, 1992; Rankinen *et al.*, 2004). Additionally, the model requires information about sub-catchment structure (number, size, reach length), physical properties of the selected sub-catchments, and inputs of N from atmospheric deposition, fertiliser application and effluent discharges. The model version INCA 1.7.12, used in this study, includes an improved procedure to calculate soil temperature under snow cover in winter (Rankinen *et al.*, 2004).

Model calibration and scenario runs

The INCA model was calibrated to both Øygard and Dalelva (Kaste, 2004) and to the Simojoki river basin (Lepistö *et al.*, 2004; Rankinen *et al.* 2002, 2004). The principles for model calibration were somewhat different. In the Norwegian catchments, the simulated mineralisation rates were set close to observed net mineralisation values (Kaste, 2004) while in the Finnish catchment, the goal was to model gross mineralisation – immobilisation (= net mineralisation) close to observed values.

In the present study, the calibrated INCA applications have been used as a basis for various scenario simulations. For the N deposition scenarios, N deposition time series for the periods 1993–95 (Øygard; Dalelva) and 1994–1996 (Simojoki) were modified to simulate possible future changes (Table 2). In this procedure, the daily deposition estimates were changed proportionally to the expected changes in annual deposition.

In the case of climate scenarios, the 1993–95 temperature, precipitation and derived SMD and HER time series were

modified according to the seasonal changes indicated in Table 3 ('delta change method'). Except for growing season length, the parameter values from the original calibrations (hydrological constants, N process rates, etc.) were retained unchanged for these simulations. The hydrological input data for the Simojoki River were derived from the results of the Watershed Forecasting and Simulation System (WSFS), a conceptual hydrological model that simulates runoff using precipitation, potential evaporation and temperature as inputs. The principles of the WSFS are based on the HBV model (Bergström, 1976). Calibration of the hydrological sub-model of INCA for the Simojoki River has been described by Rankinen *et al.* (2002).

Based on the climate change scenarios in Table 3, three-year daily temperature and precipitation values were generated for the 2050s and added as input to the WSFS model, the original input data for which cover the period 1990–2000. Observations from seven precipitation stations and three temperature stations were used, as well as water level observations for Lake Simojärvi and discharge measurements at Hosionkoski rapids and the Simojoki outlet. Before the actual climate change was simulated, a run with the original input data was conducted and model output data were scaled to obtain a water balance. Then the corrected areal precipitation values were used in the actual climate change simulation by multiplying them with the predicted change for each season (Table 3).

Results

CATCHMENT RESPONSES TO ALTERED N DEPOSITION

The two northernmost catchments, Dalelva and Simojoki, are far from the main European N emission sources and, thus, receive low levels of N deposition (2–3 kg N ha yr⁻¹). Nevertheless, the N deposition scenarios associated with the current legislation (CLE) and maximum feasible reduction (MFR) imply a further reduction of N deposition loads (Table 2). At Øygard, where the present N deposition is much higher (~17 kg N ha⁻¹ yr⁻¹), the CLE and MFR scenarios will entail a substantial reduction in external N inputs.

Given the N deposition scenarios, the INCA model indicated an overall reduction of streamwater NO_3^- concentrations at Øygard and Dalelva but not at Simojoki (Fig. 2). The reduction was most pronounced during the dormant season when NO_3^- concentrations usually peak due to low plant demand for N. At Øygard, the NO_3^- concentrations during the dormant season were predicted to be reduced by 30–40% under the CLE scenario and about

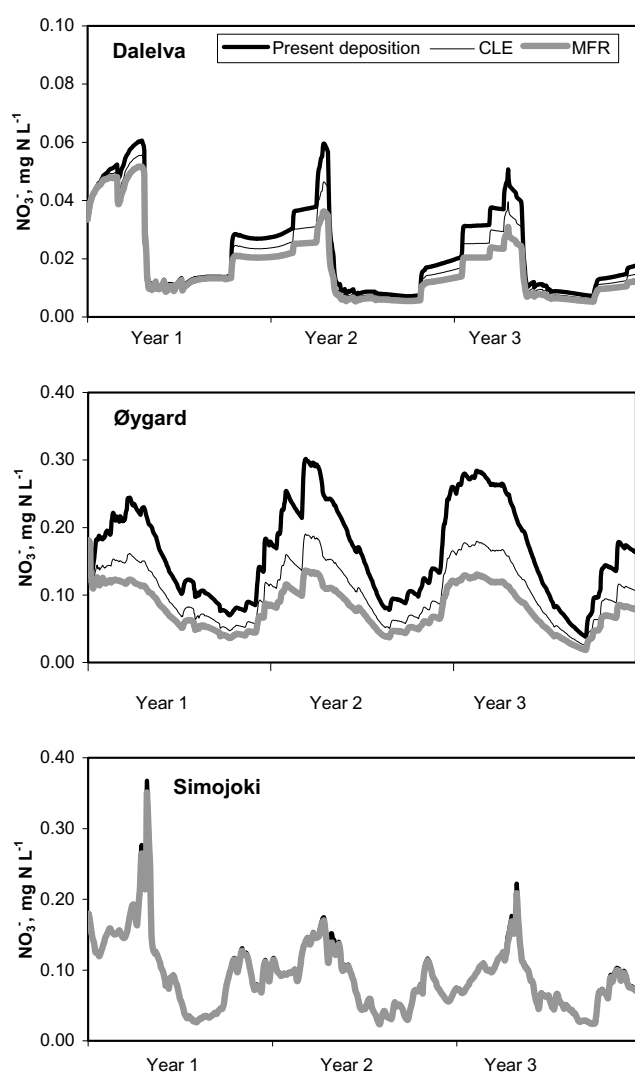


Fig. 2. Predicted changes in daily NO_3^- concentrations at Dalelva, Øygard and Simojoki in response to altered N deposition according to a) current legislation (CLE), and b) maximum feasible reduction (MFR) of N emissions. The simulations based on time series for the years 1993–95 (Dalelva and Øygard) and 1994–96 (Simojoki) modified to simulate the possible future changes given in Table 2. Note the different scales.

50% under the MFR scenario. During the growing season, when plant demand for N is high, the reduction in terms of absolute concentrations was somewhat less. At Dalelva, the change in NO_3^- concentration was minor and restricted mainly to the dormant season. The CLE scenario gave reductions in annual fluxes of NO_3^- of approximately 35 and 15% at Øygard and Dalelva, respectively. The corresponding numbers for the MFR scenario were about 50 and 25%.

At Simojoki, the responses to N deposition scenarios have

been discussed by Rankinen *et al.* (2004). The changes in the N fluxes to the sea were minor. When atmospheric deposition was reduced under the CLE scenario, the annual NO_3^- flux decreased about 1% whereas the NH_4^+ flux did not change at all. Reducing the atmospheric deposition under the MFR scenario decreased the NO_3^- flux about 3% and the NH_4^+ flux less than 1%. The main reason for the slight response at the Simojoki catchment is that N deposition is low compared to effective vegetation uptake by northern N limited forests (Table 3).

POTENTIAL IMPACTS OF CLIMATE CHANGE

Hydrology

Given the climate change scenarios, the INCA model simulated rather dramatic changes in snow accumulation and subsequently also in the seasonal flow patterns at the study sites (Fig. 3a). The most pronounced changes are to be expected at the northernmost catchments, where the maximum snow depth during winter might decrease by 50–60% at Dalelva and as much as 70–80% at Simojoki. The climate change scenario applied to Simojoki, however, implied a substantially higher increase in winter temperatures than that at Dalelva. At Øygard, the irregular snow accumulation characterising the present situation will become even more dominant under the climate change predicted.

Streamwater flow patterns, especially at Dalelva and Simojoki, would be heavily affected by the reduced snow accumulation and snowmelt might occur during the whole winter season. Additionally, the regular snowmelt flood will be less distinct and will be earlier in the spring. In many aspects, the hydrological patterns might show many similarities with the present situation at Øygard, where floods occur frequently at all seasons, and there is no distinct snowmelt flood (Fig. 3b). The flow pattern at Øygard may not change very much under a changed climate, but the flow peaks are expected to increase, especially in autumn.

The annual simulated water discharge does not necessarily reflect the annual increase in precipitation amounts, because evapotranspiration rates will increase as well, as a response to the predicted rise in air temperatures (Table 4). At Dalelva and Simojoki (high scenario), annual runoff might be slightly less because of the relatively large increase in temperature. Based on the low scenario at Simojoki, annual discharge would remain at the present level, while annual evaporation would increase by 11% under the low scenario and by 31% under the high scenario. At Øygard, the INCA model simulated a 10% increase in annual water discharge due to climate change by 2050.

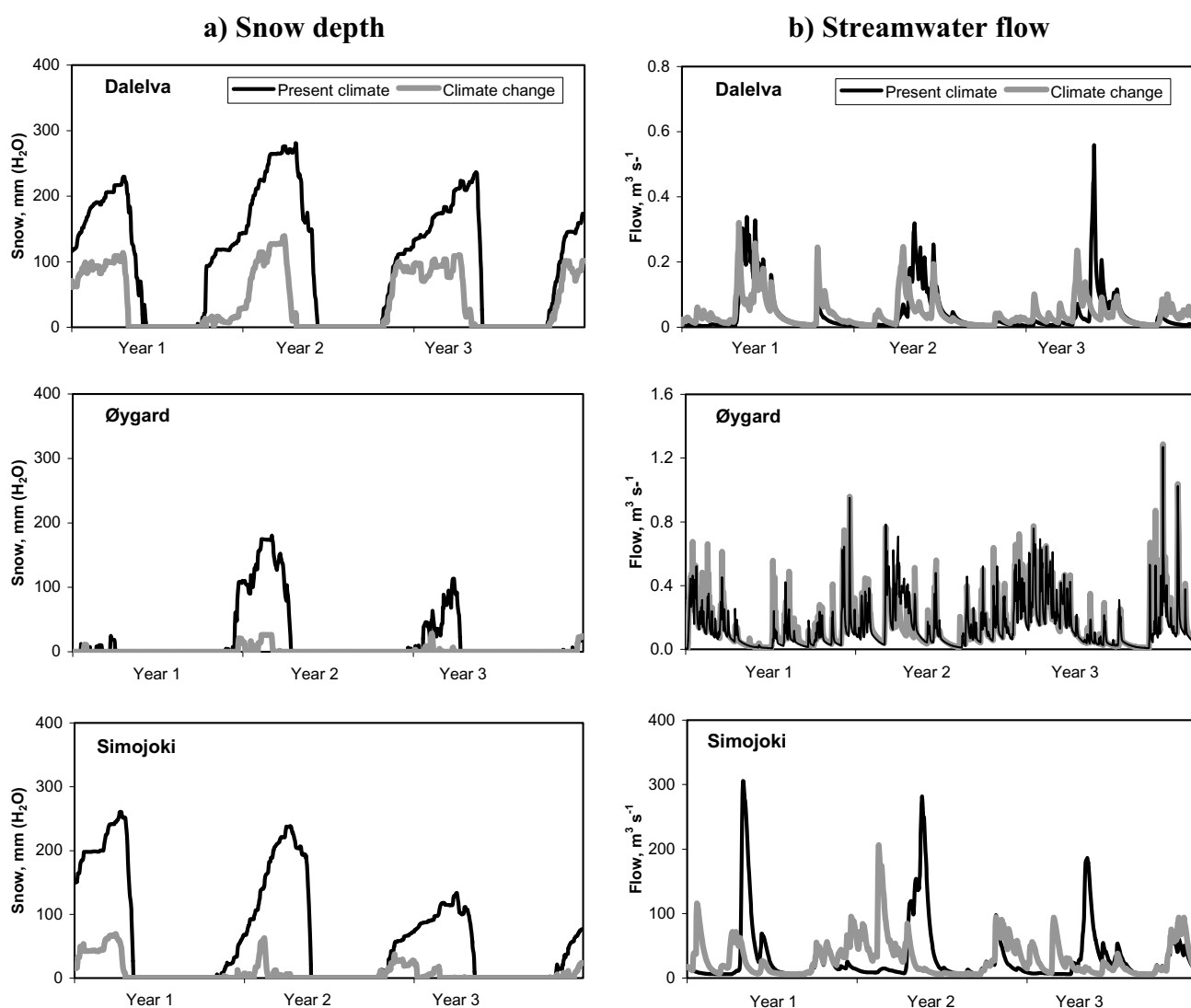


Fig. 3. Predicted changes in year 2050 in snow depth and streamwater flow following scenarios of climate change at the study sites. The simulations based on time series for the years 1993–95 (Dalelva and Øygard) and 1994–96 (Simojoki) modified to simulate the possible future changes given in Table 3. The Simojoki application is based on the HadCM3-gg high scenario.

Table 4. Predicted changes in water discharge (three-year mean; mm yr⁻¹), given the climate change scenarios indicated in Table 3. Present day is measured data from 1993–95 at Dalelva/Øygard and from 1994–1996 at Simojoki.

	Present (1993–96)	Future (2050)
Dalelva	423	421
Øygard	1790	1978
Simojoki	315	317/302 ¹

¹ Low / high scenario

Land-phase and in-stream N transformation rates

N transformation rates, both within the terrestrial catchment and in the stream, are temperature dependent. In addition, the terrestrial processes will be dependent on soil moisture content. Hence, predicted climate change might have significant impacts on the internal N processing rates within the catchments. Table 5 (scenario A) shows the simulated response of terrestrial N process rates to the changes in air temperature and precipitation predicted in 2050. The most significant change simulated by the INCA model was an increase in N net mineralisation rates; these almost doubled at Dalelva and increased by about 20% at Øygard and Simojoki (high scenario). The increased N mineralisation

Table 5. Predicted changes in N sources and sinks (three-year mean; kg N ha⁻¹ yr⁻¹) with different scenarios including climate and N deposition change. Present day is calibrated data from 1993-95 at Dalelva/Øygard and from 1994-1996 at Simojoki. Scenarios at Dalelva and Øygard: A – changed climate and present N deposition; B – changed climate and N deposition according to current legislation (CLE). Scenarios at Simojoki: Climate change; low and high. All scenarios are described in Table 2 and 3.

	DALELVA			ØYGARD			SIMOJOKI		
	Present	Scen.A	Scen.B	Present	Scen.A	Scen.B	Present	Low	High
N SOURCES									
TIN deposition	2.7	2.7	2.3	16.9	16.9	13.2	2.3	2.3	2.3
Fertiliser input	-	-	-	-	-	-	2.6	2.6	2.6
Net mineralisation ¹	3.6	6.9	6.9	15.0	18.2	18.2	26.7	28.6	31.5
N fixation	-	-	-	-	-	-	0.30	0.30	0.31
Total	5.8	8.8	8.4	31.4	34.6	30.9	31.9	33.8	36.7
N SINKS									
Plant uptake	2.3	2.7	2.5	3.2	3.3	2.2	31.3	32.8	35.4
Denitrification	0.7	0.8	0.7	3.5	3.5	2.3	0.73	0.84	0.99
Immobilisation ²	2.6	5.0	5.0	20.5	23.5	22.9	-	-	-
NO ₃ ⁻ export	0.06	0.17	0.15	3.5	3.5	2.3	0.41	0.40	0.41
NH ₄ ⁺ export	0.00	0.00	0.00	0.1	0.1	0.1	0.31	0.32	0.33
Total	5.7	8.7	8.4	30.8	33.9	29.8	32.8	34.4	37.1
Error in balance	0.6	0.9	0.8	1.1	1.2	1.6	-0.9	-0.6	-0.4

¹Ammonification + nitrification

²Estimated differently at the Norwegian and Finnish study catchments (see details in Model calibration chapter). Finnish immobilisation estimates (gross mineralisation – net mineralisation): 59.6 kg N ha⁻¹ yr⁻¹ at present, and 58.8 and 63.9 kg N ha⁻¹ yr⁻¹ under the Low and High scenarios, respectively.

was largely balanced by increased immobilisation but, at Dalelva, the model predicted a small increase in nitrification, plant uptake and NO₃⁻ leaching. At Simojoki, vegetation uptake, nitrification and denitrification increased, by 13%, 16% and 36%, respectively

Streamwater N concentrations and fluxes

The largest relative change in streamwater NO₃⁻ concentrations was simulated at Dalelva (Fig. 4a). Here, the predicted peak concentrations in winter were 20–60% higher, and the simulated summer concentrations 2–3 times higher. The latter indicates that the climate-induced increase in N mineralisation rates might exceed the sum of immobilisation and plant N demand during parts of the growing season. This, of course, depends strongly on the length of the growing season following a climate change and the actual temperature response of the N transformation processes involved. The predicted changes in NO₃⁻ concentrations and seasonal patterns were less clear at Øygard and Simojoki; future NO₃⁻ maxima and minima were near the present levels but the timing was different. At Simojoki, the N-limited forest vegetation effectively takes up available nitrogen during the growing season.

At Dalelva, the annual NO₃⁻ export might increase 2–3 times in response to the scenario for climate change towards 2050 (Table 5). However, both the present and predicted NO₃⁻ fluxes (<0.1 kg N ha⁻¹ yr⁻¹) are negligible compared to the present N losses at Øygard (3.5 kg N ha⁻¹ yr⁻¹). The modest temperature increase predicted for the Øygard area did not imply any change in the simulated NO₃⁻ export. This may indicate that N deposition is a more significant contributor to the catchment N pools than the small increase in N mineralisation caused by the altered climate. At Simojoki, increased mineralisation rates following climate change were mostly balanced by internal N retention processes and only a 6% increase in NH₄⁺ export was simulated.

COMBINED EFFECTS OF CHANGED CLIMATE AND N DEPOSITION

Finally, a combination of the climate scenario and the CLE N deposition scenario was used (Table 5; Fig. 4b). Both factors are expected to undergo changes during the next 50 years. Addition of the CLE scenario to the climate change scenario had minor effects on simulated land-phase and in-

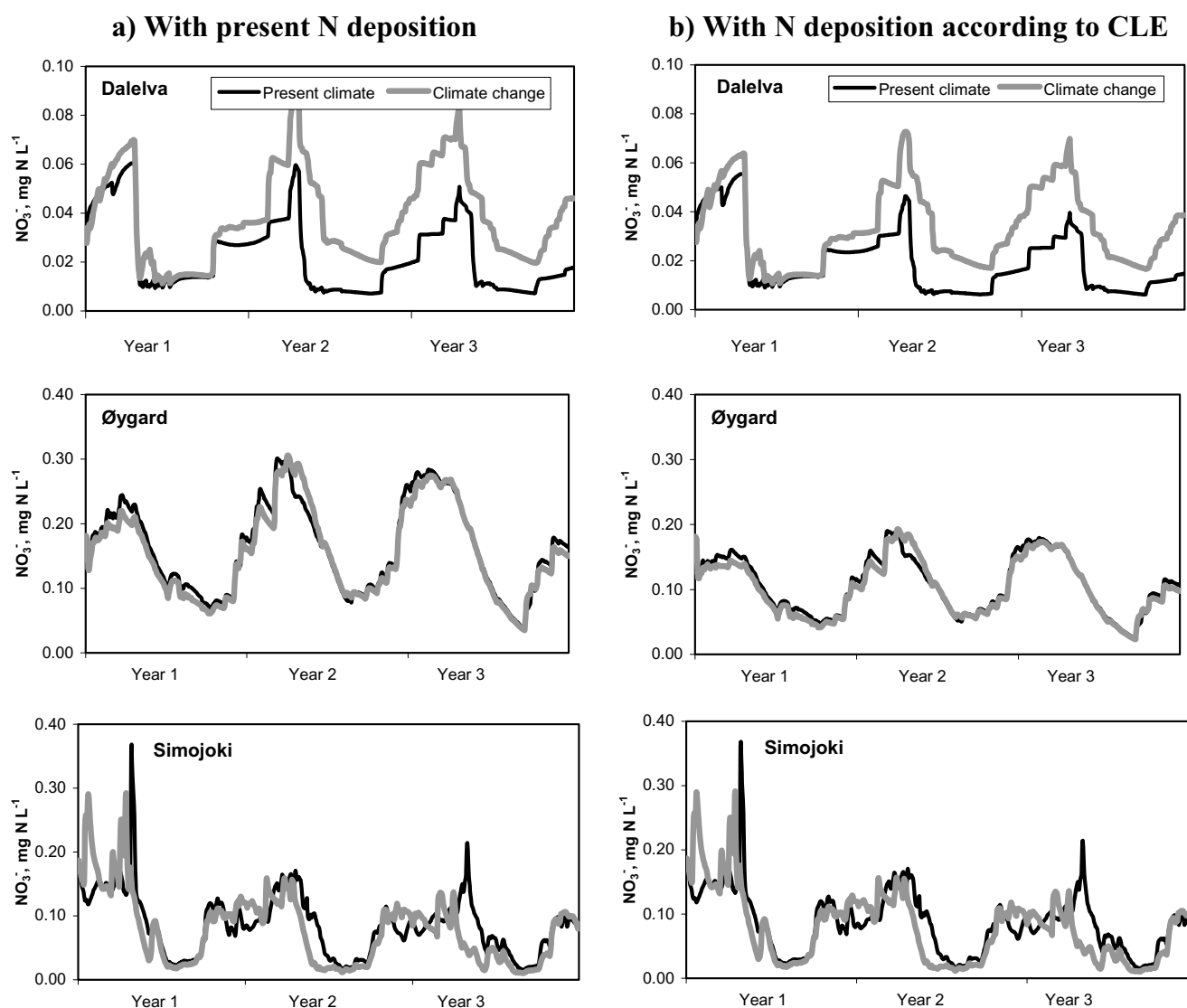


Fig. 4. Predicted changes in daily NO_3^- concentrations at Dalelva, Øygard and Simojoki under climate change: (A) With present N deposition; (B) With N deposition according to current legislation (CLE). The scenarios for altered N deposition and climate are described in Tables 2 and 3. The Simojoki application is based on the HadCM3-gg high scenario.

stream N transformation rates at Dalelva and Simojoki but significant effects at Øygard where N deposition is an important N source under present conditions (Table 5). Here, the model simulations suggested that reduced N deposition (according to the CLE scenario) will offset the climatic effects, such that future NO_3^- leaching might decrease below the present levels. The simulation of streamwater NO_3^- concentrations under such conditions suggested lower concentrations all year round, but most pronounced during the dormant season (Fig. 4b).

Discussion and conclusions

Over the next few decades, large-scale changes in climate and N deposition levels may entail significant changes in the N cycle of many terrestrial and aquatic ecosystems (e.g. Vitousek *et al.*, 1997; Schindler, 2001). If the recent agreements to control N emissions (the Gothenburg Protocol and the NEC directive) are fulfilled, there will be substantial reductions of potentially harmful N deposition over large parts of Europe. There is presently a relatively large scatter in climate scenarios produced by various global climate models (Allen *et al.*, 2000), but most model predictions for

northern Europe imply significant increases in air temperatures and precipitation over the next 50–100 years (Benestad, 2002).

The combined effects of climate change and altered N deposition on N cycling and losses in terrestrial and aquatic ecosystems are difficult to predict. Both long-term water chemistry records and catchment-scale experiments indicate that reduction of N inputs from deposition results almost immediately in reduced concentrations of NO_3^- in runoff (Wright *et al.*, 1993; Kopáček *et al.*, 1998; Tietema *et al.*, 1998). On the other hand, a future climate change may cause increased NO_3^- production from mineralisation of soil organic matter and, thus, offset decreases in N leaching obtained by decreased N deposition (Nadelhoffer *et al.*, 1992; Kirschbaum, 1995; Stottlemyer and Toczydlowski 1999a,b). Process-oriented catchment models are useful in assessing the possible impacts of these two driving forces in combination. The reliability of model outputs, however, depends strongly on the parameterisation of key N transformation processes and on their responses to altered temperature and soil moisture contents. Here, catchment-scale experiments and long-term data sets provide important constraints for the modelling of the whole-ecosystem response.

Under future climate change scenarios for the Norwegian and Finnish study catchments, the INCA model predicts markedly reduced snow accumulation over the next 50 years, both in terms of duration and quantity (Fig. 3a). Moreover, the occurrence of winter rainfall and melting periods will be more frequent. Thus, several small floods may well replace the large snowmelt flood occurring regularly in late spring. These predictions are in accordance with other model simulations (Hessen and Wright, 1993; Lepistö and Kivinen, 1997) and also with observations from long-term records (e.g. Reihan, 2002). In summer, increased air temperature will lead to higher evapotranspiration rates. At Simojoki and Dalelva, an increase in soil moisture deficit and a decrease in streamwater flow (mean; –32% and –56%, respectively) will occur from June to August. At Øygard, the predicted increase in summer precipitation outweighs the effects from increased evapotranspiration.

The predicted changes in snow accumulation and annual flow patterns have several implications for N cycling and losses in the study catchments. Paradoxically, increased air temperatures following global warming can lead to colder soils because of reduced snow cover in winter (e.g. Groffman *et al.*, 2001). This effect will probably be most pronounced in the northernmost catchments, Simojoki and Dalelva, currently characterised by long and stable winters. In an experiment conducted in a temperate deciduous forest at Hubbard Brook, USA, Groffman *et al.* (2001) found that

snow removal promoted soil freezing which in turn led to significant increases in root mortality, soil NO_3^- concentrations and hydrological fluxes of carbon, nitrogen and phosphorus. This general pattern is also observed in long-term records, where high NO_3^- concentrations and drainage losses have been observed following anomalously cold periods in winter (Mitchell *et al.*, 1996; Monteith *et al.*, 2000; Kaste and Skjelkvåle, 2002). Another effect of a more irregular snow cover in the future is more frequent freezing and thawing cycles that might affect N transformation processes during winter. Several studies have indicated very high, episodic rates of mineralisation, nitrification and denitrification associated with such periods (e.g. Goodroad and Keeney, 1984; Ryan *et al.*, 2000).

These mechanisms are difficult to simulate within INCA, because the responses of each N process included in the model are positively correlated with temperature, whereas direct freezing effects on soils and episodic N transformations during freezing–thawing cycles are not accounted for. Therefore, the simulated NO_3^- leaching by the model will depend on the pre-set temperature response of each individual process and the hydrology that drives N through the various compartments of the system. Field measurements and isotope studies in seasonally snow-covered alpine catchments indicate that N is accumulated in the soil water during the dormant season, and is then flushed during an early phase of the snowmelt flood (Arheimer *et al.*, 1996; Williams *et al.*, 1998; Campbell *et al.*, 2002). This suggests that N production (N deposition, mineralisation) dominates over N retention (denitrification, uptake, immobilisation) during this season, and that hydrology to a large extent controls the magnitude of NO_3^- leaching from these ecosystems.

Besides the effects on the hydrological regime, the predicted temperature increase will affect several aspects of N production, uptake and mobility in catchments. Most N transformation processes are temperature and moisture dependent and increased temperatures in all instances lead to higher process rates. There are, however, indications that the various processes have different temperature responses (Q_{10} values; i.e. the factor change in rate following a 10-degree change in temperature) along the temperature gradient. In a review of several laboratory-based experiments, Kirschbaum (1995) found that the temperature sensitivity of decomposition relative to net primary productivity was much greater at low soil temperatures. Along a temperature gradient of 0–10–20 °C, the Q_{10} value of decomposition decreased from nearly 8 to 4.5 and 2.5, respectively. Hence, the sensitivity of decomposition around 20 °C was more similar to that of net primary production. This general pattern of high temperature response by

decomposers near 0 °C has important implications for the effects of climate change on N mineralisation and losses in northern catchments.

A catchment-scale experiment, CLIMEX, performed at Risdalsheia in southernmost Norway, demonstrated that a three-year increase in CO₂ level and temperature (2–5 °C above ambient) in an enclosed forested catchment increased the inorganic N leaching by a factor of three (Wright, 1998). This was explained by increased decomposition of soil organic matter and mineralisation of organic nitrogen to inorganic species (Van Breemen *et al.*, 1998; Verburg and Van Breemen, 2000). These results suggest that N mineralisation and nitrification may have a more pronounced response to a 2–5 °C increase in temperature than e.g. N uptake, denitrification or N immobilisation. The temperature response (Q_{10}) of N mineralisation was about 3, which is within the range reported by Kirschbaum (1995). Examination of long-term records has also revealed a strong temperature control on the leaching of inorganic N. Warm and dry summers can generate high NO₃⁻ peak discharges, especially when followed by a hydrological flushing period (Reynolds *et al.*, 1992; Murdoch *et al.*, 1998; Van Miegroet *et al.*, 2001).

Both laboratory and large-scale experiments, thus, suggest that decomposition and N mineralisation respond more quickly to a temperature increase than the corresponding N retention processes, at least during an initial phase of the warming process. In the recently adapted version of the INCA model used here (Rankinen *et al.*, 2004), it is possible to apply individual temperature response functions (Q_{10} values) to different land cover classes, but not to individual N transformation processes. This option is included in a recently developed (but not yet implemented) test version of INCA. Still, the dynamic temperature response suggested by Kirschbaum (1995) will be difficult to simulate, because each temperature response function is based on a fixed Q_{10} value along the entire temperature gradient. Further, there will always be a high degree of uncertainty associated with the temperature response of various N processes (especially N immobilisation) on a catchment scale.

According to the INCA simulated climate change scenarios, the largest changes are expected in the northernmost catchment, Dalelva. Here, the predicted temperature increase might involve a doubling of the mineralisation rate (from 3.6 to 6.9 kg N ha⁻¹ yr⁻¹), which may greatly increase the availability of inorganic nitrogen in the soils (Table 5). This is more than twice the level of the present atmospheric deposition in this region. According to the model simulation, the increased N supply will be balanced largely by increased plant uptake (longer growing season, increased growth rates) and immobilisation.

However, small increases in denitrification and NO₃⁻ leaching rates are also predicted. Compared to the low initial NO₃⁻ leaching level, the NO₃⁻ export rates might increase by a factor of nearly three. At the Simojoki and Øygard catchments, the relative increase in mineralisation rates due to climate change were less pronounced (approximately 20%). Here, the increased N availability was to a large extent balanced by internal N sinks in the model. No increases in NO₃⁻ leaching were predicted, and only a slight increase (6%) in NH₄⁺ leaching at Simojoki. However, these relationships between climate-induced N production and subsequent N retention depend strongly on anticipated temperature response functions for the processes involved. Given a slower or ineffective response from one of the N sink processes, as demonstrated for example in the CLIMEX project (Van Breemen *et al.*, 1998; Wright, 1998), a larger fraction of the extra N mobilised by mineralisation might be exported to freshwaters and, thus, to marine coastal waters. Here, catchments enriched with N from several decades with elevated N deposition (e.g. the Øygard catchment) seem to be more susceptible to climate-induced N leaching than N limited ecosystems such as Simojoki and Dalelva (Wright *et al.*, 1998).

A large fraction of the increased NO₃⁻ export following climate change is expected to take place during the dormant season when plant demands for N are low (Fig. 4a). In addition, NO₃⁻ peaks might occur earlier in spring, as indicated for the Simojoki River. In the Dalelva Brook, slightly elevated NO₃⁻ concentrations were also predicted during the growing season. At present, both Dalelva Brook and Simojoki River can be classified as N-limited (stage 0 of Stoddard's classification; Stoddard, 1994), whereas the Øygard catchment falls between stage 1 and 2, which denotes an N-saturated system with moderate to high annual losses (Stoddard, 1994; Kaste and Skjelkvåle, 2002). If N emissions are reduced in accordance with the current legislation, this will have a major effect on streamwater NO₃⁻ concentrations at the Øygard catchment, even in combination with future climate change (Fig. 4). As such, significant improvements with respect to streamwater acidity and coastal N input might be expected within this region following this N reduction scenario. At the more remote Dalelva and Simojoki catchments, the expected N deposition reductions will be small compared to the internal N recycling processes and climate change might to a large extent offset the effects of reduced N deposition.

Several factors will determine the N status of the study catchments in the next 50 years. In addition to the possible short-term effects from climate and deposition change discussed above, the long-term effects might be even more important (e.g. N accumulation v. storage capacity; size of

N pools available for mineralisation, retention processes). Besides transient climate scenarios, a simulation of such long-term climate change effects requires more research and model development, because INCA in its present state lacks a dynamic soil organic pool resulting from the long-term balance between N accumulation and release processes.

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